

Proceedings of the Eurosensors XXIII conference

Towards embedded control for resonant scanning MEMS micromirror

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Abstract

This paper describes the design and realization of an electrostatic actuated MEMS mirror operating at a resonance frequency of 23.5 KHz with a PLL feedback loop. The design is based upon a thorough understanding of the (non-linear) dynamical behavior of the mirror. Using an external position sensitive device (PSD) the proper working of the PLL is demonstrated.

Next we study the possibility to replace the PSD sensor with an embedded capacitive phase-angle sensor. We show measurements of capacitance changes with large parasitic influences while actuating the mirror in a feed forward mode. This demonstrates the feasibility of a fully embedded control for a resonant scanning MEMS mirror.

Keywords: MEMS micromirror; laser display; raster scanning, capacitive tilt-angle sensor; PLL

1. Introduction

Small electronic devices such as mobile phones (smart phones), PDA's, and multi-media players, are becoming increasingly more popular. Consumers can access and exchange information at any time at any place. Whereas these devices become smaller and at the same time the amount of information increases, there is a need for a new technology that is both small and at the same time can display a large amount of information in a convenient way. Miniature Laser Projection or Pico projection is one of the most promising technologies for this need [1, 2]. First products are already appearing on the market as stand-alone products. The flying spot architecture is being regarded as the most promising technology for a low cost, small size module to be embedded in a mobile phone. Key enabler is the MEMS mirror that –in theory- can meet the challenging cost, size and power requirements. However, despite the 20 years since earliest versions of a MEMS mirror there is currently no mass produced MEMS mirror really suitable for an embedded laser projector. Still many issues need to be solved to go from one working device to mass produced devices.

2. Design requirements and challenges for scanning laser projection

For laser scanning projection from a hand held consumer product, the key drivers are: good image quality, small size, low power consumption and of course low cost. An excellent overview of the challenges these requirements have on the design is given elsewhere [3]. Here, we want to recall some of their most relevant results and the consequences for our design:

- A SVGA resolution (800x600 pixels) at a refresh rate of 60 Hz requires a line frequency of 36 kHz. Using bidirectional scanning leads to an operating frequency of at least 18 kHz along the fast-axis.

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- The number of resolvable spots depends linearly on the product of the mechanical scan-angle and the diameter of the scanning mirror, θD , which must be larger than 10 [deg.mm] [4]
- The inertial forces are very large due to the high operating frequency, resulting in a significant dynamic deformation of the mirror. The deformation of optical surfaces should however be less than $\lambda/10$, or 40 nm.

For a low-power device capable of bidirectional laser scanning at high frequency, a resonance mode is required, with a high Q-factor, typically at least 200.

To obtain a high θD value, it is easier to increase the scan-angle (θ) than to increase the diameter (D), as long as the maximum stress level due to elastic deformation in the mirror's suspension is within limits. On the other hand, a small mirror requires a more stringent opto-mechanical alignment of the optical components. On top of that, additional optical components might be required to image the laser beam onto a projection screen. Based upon some first-order calculations, the diameter of the mirror is selected to be ϕ 1.0 [mm]. This means that the mechanical scan-angle of the fast axis should be at least 10 degrees.

The most important architectural design choice to be made is between a single mirror with two rotation axis (1x2D) and two individual mirrors each having a single rotation axis (2x1D). Obviously, the dual axis mirror is ideal, because it saves an additional mirror, which reduces the alignment effort, volume claim, and optical losses [5]. At the same time it also has some major drawbacks. To combine the requirements above in a single 2D mirror puts very high strain on the mechanical design and increases the complexity of the design which does not outweigh the gains. This paper describes work done on the fast-axis mirror in a system based on the two-mirror (2x1D) architecture.

3. Mechatronic micromirror design

The requirement of a resonance mode for the fast-axis laser scanning, is implemented in micromirror designs with a pair of torsion beams i.e. 'torsion-beam scanners'. The pair of torsion beams should ideally provide a single rotational degree-of-freedom (DOF) with both:

- - a large allowable strain to allow for a large tilt angle, and
- - a well-defined but finite stiffness to provide an eigen-frequency, and
- - an infinite stiffness in all five other DOFs to suppress unwanted rigid-body motions

Combining these contradicting requirements into a single pair of beams leads to compromises, at the expense of the dynamical performance of the device. The solution is found in separating stiffness from suspension: The design presented in Fig. 1, Fig. 2 has four cantilever beams to provide a well-defined stiffness around a single rotation axis. This rotation axis is defined by two thin and short support beams. This design nicely suppresses the out-of-plane translation mode and rocking mode, which are the two most important parasitic modes from an optical engineer's perspective.

We designed a process based upon industrially proven process steps to accurately control critical parameters and fabricated a mirror using cantilever beams, out-of-plane support beams and a rhombus shaped enforcement structure to keep the mirror deformations below $\lambda/10$, or 40 nm (Fig. 2).

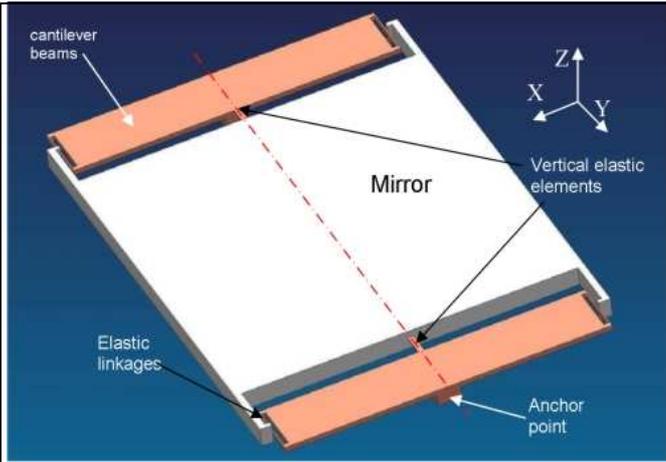


Fig. 1: Schematic of the mirror design with rotation around the vertical elastic elements in the y-axis

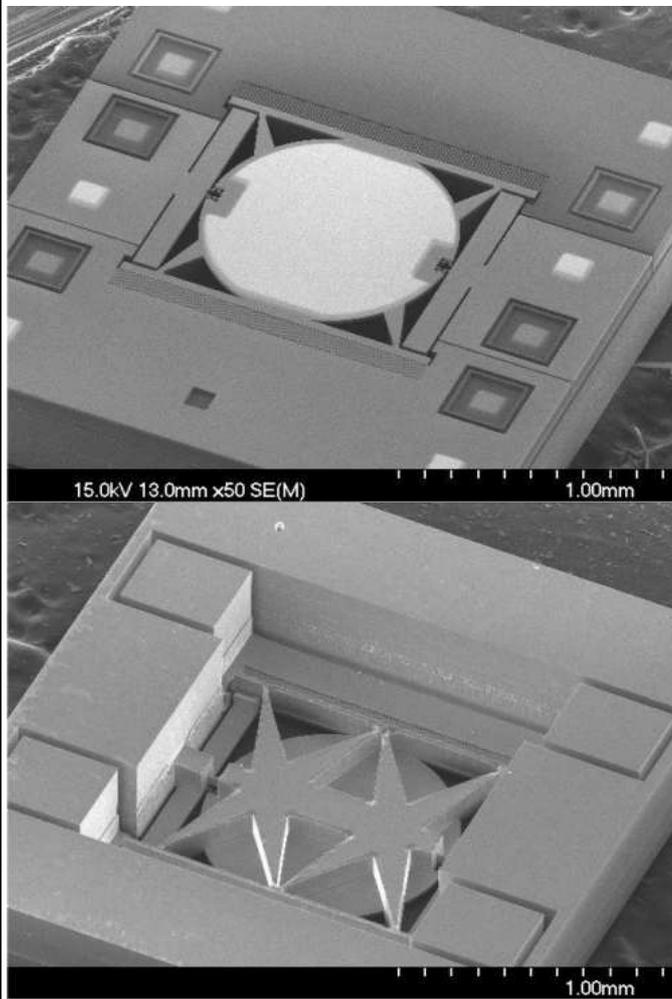


Fig. 2: SEM images of processed mirrors. (top) mirror-side. (below) Back-side.

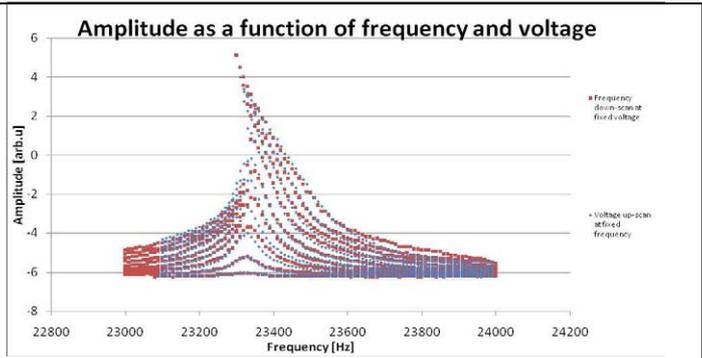


Fig. 3: Scan angle as a function of frequency and voltage.

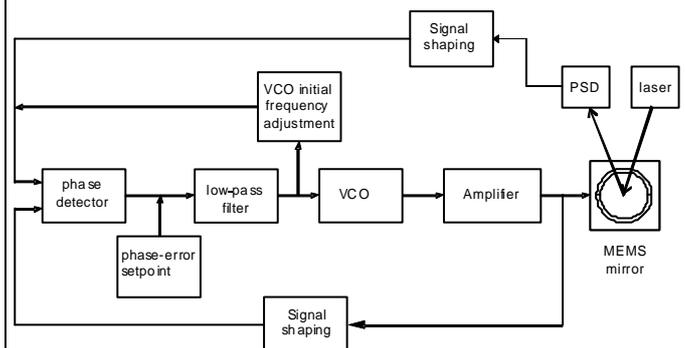


Fig. 4: Schematic of mirror with optical PLL control

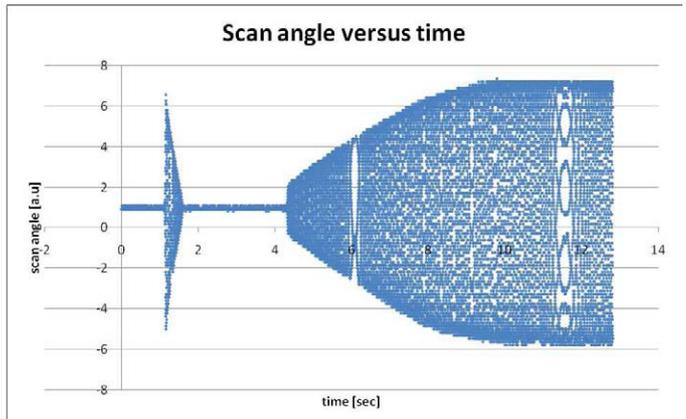


Fig. 5: Measured scan angle of the resonant scanning micromirror with PLL-control and optical sensor.

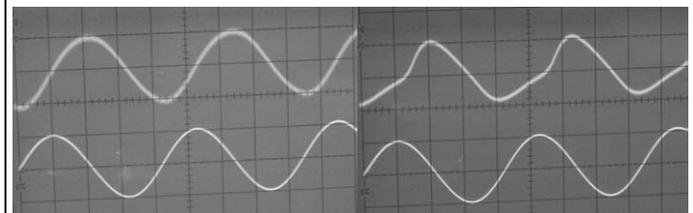


Fig. 6: Oscilloscope pictures of the signal through the comb-structure capacitance of the micromirror. Upper trace is the measured signal indicating resonance, lower trace is the actuation signal. (left) below resonance frequency. (right) at resonance.

4. Measurements with fast-axis resonant scanning MEMS micromirror

Measurements on fabricated devices show a well defined resonant mode of operation at 23.5 kHz while exhibiting only small parasitic resonance modes.

The high Q-factor results in a sharp resonance peak and makes the device susceptible to changes in resonance frequency: from batch to batch, device to device, or within one device in time. The mirror is operated in its resonant mode using an electrostatic out-of-plane comb drive actuator. This type of actuator however leads to a strong non-linear behavior at large scan angles (Fig. 3). Therefore a feedback loop method with a Phase Locked Loop (PLL) is required to compensate for these changes and non-linear dynamics [6]. The phase must be accurately measured to synchronize the switching of the laser sources with the motion of the mirror, whereas the amplitude must be controlled to achieve a stable image.

As a first step the phase is measured using an optical position sensitive device (PSD). The proper working of the PLL in Fig. 4 is demonstrated in Fig. 5. For a certain actuation voltage the actuation frequency is decreased from a frequency above the resonance frequency, until the amplitude of the tilt-angle has increased sharply around resonance, as in Fig. 3, and the PSD measured phase angle is equal to the setpoint value and locked.

The next step is to use an embedded sensor: using the capacitance change of comb-drive of the MEMS mirror directly as a phase sensor. Since these changes are extremely small, the design of the comb-drives needs to be optimized specifically for this purpose. Fig. 6 shows oscilloscope pictures of the measured results. The upper trace is the measured signal through the comb-structure capacitance of the micromirror picked up with the common synchronous detection method. The lower trace is the actuation signal applied to the comb-drive. Fig. 6 (left) is measured while actuating below resonance frequency, Fig. 6 (right) is operated at resonance. Large unfavorable effects are present e.g. large parasitic capacitances, actuation with high-voltages and high-bandwidth. The results demonstrate in principle the feasibility of an embedded capacitive phase sensor by measuring capacitance changes during a frequency sweep in an open-loop mode of the MEMS mirror. But, the current design of the comb-drives needs to be optimized specifically for the measurement of small capacitance changes.

5. Conclusions

This paper describes the design and realization of an electrostatically actuated laser scanning MEMS micromirror in a system based on the two-mirror (2x1D) architecture. Operation at a resonance frequency of 23.5 KHz with an external PSD sensor and a PLL feedback control is demonstrated. We show measurements of capacitance changes with large parasitic effects, while actuating the mirror in a feed forward mode. This proves the feasibility of replacing the PSD and using the embedded capacitance sensor for a fully embedded control for the resonant scanning MEMS mirror.

Acknowledgements

This work has been sponsored in part by the Dutch government within the framework MEMSland. The authors want to thank Silex Microsystems for fabricating the devices and our colleagues for all their valuable contributions.

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